DIVISION S-7—FOREST AND RANGE SOILS

Cumulative Effects of Nitrogen, Phosphorus, and Potassium Fertilizer Additions on Soil Respiration, pH, and Organic Matter Content[1]

KEITH VAN CLEVE AND TERRY A. MOORE[2]

ABSTRACT

Cumulative effects of annual additions of NH_4NO_3 (111 kg/ha N), treble superphosphate (55 kg/ha P), and KCl (111 kg/ha K) on aspen (*Populus tremuloides* Michx.) soil respiration, pH, and soil organic matter content were examined. Total fertilizer additions from fall 1969 through spring 1975 were 777 kg/ha N and K and 385 kg/ha P.

The main effect of N and P additions was to increase soil biological activity by up to 42% and 33%, respectively, with the greatest increases occurring at the 15- to 30-cm soil depth. For K, a 21% reduction in soil biological activity occurred at 0- to 15-cm, while a 20% increase was found at 15- to 30-cm. Fertilization with N and P increased but K showed no effect on surface soil organic matter content. Subsurface soil (15- to 30-cm) organic matter content was not affected by any treatment. Higher soil organic matter content probably resulted largely from greater aspen growth response to N. Increased soil biological activity was attributed to a combination of increased soil organic matter content and improved levels of soil N and P.

Treatment with N, K, or N + K reduced soil pH, possibly because of microbial nitrification of NH_4^+ associated with uptake by aspen of NH_4^+ and K^+ with replacement of H^+ in the soil.

Additional Index Words: **soil microbial activity, forest fertilization, soil organic matter, acidity, aspen.**

IN AN EARLIER ARTICLE (Van Cleve, 1973), the growth response of 15-year-old quaking aspen (*Populus tremuloides,* Michx.) in stem diameter and height to repeated addition of N (NH_4NO_3), P (treble superphosphate), and K (KCl) was described. The original aspen forest had been destroyed by fire which generally consumed all of the forest floor. Given the shallow rooting habit of aspen, with the bulk of roots to be found in the forest floor and in the upper 15-cm of mineral soil, it was hypothesized that the forest floor was the principal reservoir of N available for tree nutrition. It was further assumed that, since the forest floor had been destroyed by fire, N available for new growth would be in critically short supply. On the other hand, P and K would not have been lost through destruction of the forest floor except by leaching through the soil profile. Yearly additions of fertilizer since 1969 confirmed the dominance of growth response to N.

However, the question remained of the effect of annual additions of nutrients over a number of years on other ecosystem components and processes. In particular, the impact of increased soil nutrient levels on soil biological activity may be of crucial long-term importance with regard to decomposition of soil organic matter. If heavy applications of selected nutrients depressed soil organic matter decomposition, then availability of other essential nutrients might be restricted. On the other hand, stimulation of soil biological activity might also reduce availability of nutrients in the soil by immobilization in microbial tissue. Finally, stimulation of microbial activity may also be associated with more rapid mineralization of organic matter and turnover of nutrients not found in applied fertilizers. In this regard, timing of fertilizer application may be important. If the rate of organic matter mineralization is stimulated by fertilization, nutrients may be released at a rate higher than that of uptake by plants, resulting in increased loss of nutrients by leaching.

The objective of this study was to assess the impact of repeated applications of N, P, and K fertilizers on soil biological activity, as indicated by soil respiration. Since remoistened, air-dried, sieved soil samples were analyzed, the estimates of biological activity should be considered only as indices of response of the soil microbial population to repeated additions of fertilizer.

DESCRIPTION OF STUDY AREA

The study area is in the upper Chena River Valley approximately 40 km northeast of Fairbanks, Alaska, on a well-drained lowland site. A forest cover about 35 years old had been destroyed by fire in 1956, and the present cover probably originated from sprouts from surviving root stock. As a result of the fire, the forest floor was completely destroyed. The newly established vegetation is rooted in the surface 30 cm of mineral soil. At the time of the first assessment of growth response to nutrient additions (1971), unfertilized aspen regeneration averaged 1.7 cm in diameter and 1.8 m in height. Average stem density was 23,875/ha and basal area was 8.1 m^2/ha. Soil in this generally level area is the deep (>2 m), well-drained, Salchaket silt loam (Typic Cryofluvent). Mean annual precipitation and temperature for the Fairbanks area are 28.7 cm and -3.4°C.

FIELD METHODS

In the fall of 1969, a complete factorial fertilizer trial was established using a randomized block experimental design replicated three times and employing 0.02 ha plots. NH_4NO_3 (111 kg/ha N), treble superphosphate (55 kg/ha P), and KCl (111 kg/ha K) were broadcast seven times, once at the end of the 1969 growing season and before tree growth started in the spring of each succeeding year from 1970 through 1975. Thus, totals of 777 kg/ha N and K and 385 kg/ha P had been applied through the 1975 growing season.

In fall 1975, four points were established in a systematic fashion at least 5 m from each plot corner along diagonal lines between opposite plot corners. Using a 6-cm diam. bucket auger, samples of 0- to 15-cm and 15- to 30-cm depths of mineral soil were obtained from each point. Fixed sampling depths were employed to encompass the most dense zone of tree rooting (0- to

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[2]Professor of Forest Soils and Graduate Student, respectively, Forest Soils Lab., Univ. of Alaska, Fairbanks, AK 99701.

Table 1—Main effects of fertilizer treatments on selected soil properties and soil biological activity.

Treatment	μliter O_2 uptake 100 g^{-1} • hr^{-1} respiration		% Organic matter		pH	
Level†	0	1	0	1	0	1
		N				
0-15 cm	223.3	258.5	4.4	5.0	6.1	5.9**
15-30 cm	53.9	76.4**	2.5	2.7	6.1	6.1
		P				
0-15 cm	217.3	264.4	4.2	5.1**	6.0	6.0
15-30 cm	55.9	74.3**	2.5	2.6	6.1	6.1
		K				
0-15 cm	269.1	212.6*	4.5	4.8	6.1	5.8**
15-30 cm	59.1	71.1	2.6	2.6	6.4	5.8**

† 0 = 0 level for treatment, 1 = full level for treatment.
* Difference between 0 level and full treatment level significant at 5% level of probability.
** Difference between 0 level and full treatment level significant at 1% level of probability.
Main effect comparisons involve comparison of all treatments including a particular nutrient compared with all treatments where the nutrient was not included.

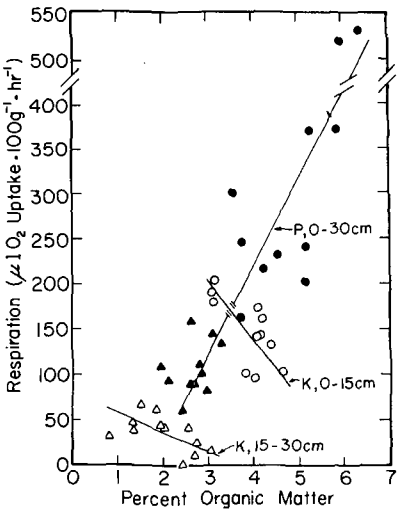

Fig. 1—Soil respiration in relation to soil organic matter content. ● phosphorus treatment at 0-15-cm depth, ○ potassium treatment at 0-15-cm depth, ▲ phosphorus treatment at 15-30-cm depth, and △ potassium treatment at 15-30-cm depth.

15-cm) and the next 15 cm (lower portion of the rooting zone) in order to assess the impact of biological activity associated with root growth on soil properties. Samples were separately placed in plastic bags in the field and transferred to the laboratory for processing. The four samples each of the 0- to 15-cm and 15- to 30-cm depths of mineral soil from each replicate plot and treatment were subsequently analyzed.

LABORATORY METHODS

Samples were air dried at room temperature for 3 weeks, ground to pass a 2-mm sieve, and stored in plastic bags.

Duplicate samples for estimation of respiration rate were moistened to the 1/3 atm moisture content (dry-weight basis), an optimum level based on previous estimates of soil respiration.

Table 2—Average soil respiration, percentage organic matter, and pH for factorial fertilizer experiment.†

Treatment	μliter O_2 uptake • 100 g^{-1} • hr^{-1} respiration		% Organic matter		pH	
Depth	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
C	179.8* (35.7)	23.1 (7.4)	3.5 (0.2)	2.5 (0.3)	6.4 (0.1)	6.3 (0.1)
K	176.8 (31.2)	35.6 (5.8)	4.0 (0.2)	2.0 (0.2)	5.9 (0.1)**	5.9 (0.1)**
P	327.5 (39.7)*	108.4 (8.1)**	4.7 (0.3)**	2.6 (0.3)	6.2 (0.1)**	6.5 (0.1)
PK	209.3 (30.0)	48.5 (10.5)	5.3 (0.6)*	2.8 (0.3)	5.9 (0.1)**	5.7 (0.1)**
N	258.4 (61.2)	55.8 (6.4)**	4.6 (0.3)**	2.5 (0.1)	6.1 (0.1)**	6.5 (0.0)
NK	254.8 (37.1)	109.2 (19.0)**	4.9 (0.3)**	2.9 (0.1)	5.6 (0.1)**	5.8 (0.1)**
NP	339.7 (85.4)	49.2 (17.3)	5.2 (0.8)	2.6 (0.2)	6.0 (0.1)	6.3 (0.1)
NPK	209.5 (45.8)	91.3 (12.5)**	5.0 (0.7)'	2.6 (0.1)	5.8 (0.1)**	5.9 (0.1)**

† For each variable, means (± standard error of mean) for each treatment compared with control using t-test. Mean is calculated on basis of four replicate field samples collected for each depth from each of three blocks.
* Difference between treatment and control significant at 5% level of probability.
** Difference between treatment and control significant at 1% level of probability.

Moistened soil was incubated at 20°C for 20 hours in a controlled temperature incubator. Respiration rates (at 20°C for 2 hours) were estimated using a Gilson respirometer and methods described by Van Cleve and Sprague (1971). Respiration rates were expressed as μliter O_2 uptake/100 g oven dry weight of soil/hour.

Selected physical and chemical properties of all mineral soil samples were assessed at this time in order to provide an estimate of the variation in substrate quality across the study area resulting from treatment. Soil texture was determined by the hydrometer method (Day, 1965) to determine possible variation in soil moisture regime. Total soil N was determined by the macro-Kjeldahl method modified to include NO_3^- and NO_2^- (Bremner, 1965), total P, and saturation paste pH by methods described by Van Cleve and Viereck (1972). Exchangeable K^+ was determined on neutral 1*N* NH_4Ac extracts of soil samples using an atomic absorption spectrophotometer. Soil organic matter was estimated by weight loss on ignition at 400°C (Jackson, 1958). Chloride analysis was conducted on 1:1 soil-filtered extracts using $AgNO_3$ titration and chromate indicator (Jackson, 1958). Sufficient analytical replication for each sample was carried out so that differences between high and low values were < 5% of minimum values.

Estimates of respiration, physical, and chemical properties of the soil were subjected to analysis of variance using the UCLA Biomedical Computer Program BMDO8V. The data was analyzed using a randomized complete block design with a factorial arrangement. The 5% level of probability was used to accept or reject the null hypothesis.

RESULTS

Soil respiration results generally showed marked but nonsignificant increases in respiration for N and P, significant decreases for K in the 0- to 15-cm soil level, and increases for N, P, and K at 15- to 30-cm (Tables 1 and 2). Regardless of treatment, highest respiration was generally encountered in the 0- to 15-cm level. All surface soil (0- to 15-cm) had markedly higher soil organic matter content than subsurface soil (15- to 30-cm). Fertilization with P and N produced significant increases in surface soil organic matter, but nutrient addition did not change subsurface soil organic matter content (Tables 1 and 2). Applied N and K

Table 3—Summary of selected soil chemical properties from fertilized and control treatments.†

	% N‡		% P		K^+ meq/100 g		Cl^- meq/100 g	
Depth, cm	C	F(N)	C	F(P)	C	F(K)	C	F(K)
0–15	0.054(0.004)	0.082(0.004)	0.11(0.01)	0.14(0.01)	0.14(0.02)[d]	0.41(0.04)	0.004(0.001)[f]	0.086(0.028)[g]
15–30	0.028(0.001)	0.035(0.002)	0.09(0.00)[c]	0.10(0.01)[c]	0.11(0.01)[de]	0.18(0.03)[e]	0.009(0.004)[f]	0.106(0.025)[g]

† Treatment for which analysis conducted is indicated as follows: F(N) = fertilized, NH_4NO_3 alone; F(P) = fertilized, treble superphosphate alone; F(K) = fertilized, KCl alone.

‡ Means ± standard error of mean associated with same superscript letter are not significantly different at 5% level of probability using *t*-test. All other combinations of means are significantly different. Comparisons only made within control or fertilized between depths and between control and fertilized within a depth interval. No comparison was made between elements.

markedly reduced soil pH at 0- to 15-cm and K at 15- to 30-cm, while P showed little or no effect at either depth. The lowest pH value (5.6) was encountered for the NK treatment (Table 2). Clay content was greater at the 0- to 15-cm than at the 15- to 30-cm depth. In general soil texture was similar across the experimental site and this would be expected to have a uniform impact on soil biological activity, nutrient dynamics, and tree growth.

For the combined 0- to 30-cm P data set, an r^2 of 0.79 was found for the relationship between respiration and percentage soil organic matter (Fig. 1, Tables 1 and 2). Values of 0.66, 0.71, and 0.58 for r^2 were obtained for this relationship (combined 0- to 30-cm data) in the N, PK, and NK treatments, respectively. No correlation was found between respiration and organic matter content for the NPK treatments. In the case of K, increasing soil organic matter was associated with decreasing respiration rate. Strongest negative correlation ($r^2 = 0.54$) was found for the 0- to 15-cm depth, while a weak negative correlation ($r^2 = 0.28$) was encountered for the 15- to 30-cm depth (Fig. 1).

DISCUSSION AND CONCLUSIONS

In an earlier discussion of the importance of substrate quality with regard to soil decomposition processes, a distinction was made between primary and secondary substrate quality (Van Cleve, 1974). Substrate was considered in a broader context than from the classical point of view. Primary substrate quality can be considered an integrative measure of physical, chemical, and biochemical soil properties with regard to their impact on organic matter decomposition. Secondary substrate quality reflects the physical, chemical, and biochemical characteristics of organic matter introduced into the soil or the decomposability of the material. In the present study, we initially manipulated three chemical components of the primary substrate, namely the levels of soil N, P, and K. In addition significant quantities of chloride (Cl^-) and calcium (Ca^{2+}) were added. The generally marked increases in levels of these nutrients and Cl resulting from fertilization for both sampling depths is indicated in Table 3. Increases in the 0- to 15-cm level ranged from about 1.3-fold for P to 21.5-fold for Cl. As previously mentioned, N had the greatest effect with regard to growth response in the young growth aspen forest (Van Cleve, 1973). Analysis of data (individual treatment effects) indicates that up to twice the tip increment and 2.8 times the diameter increment occurred at those sites treated with N compared with the control. Measurements of selected tree crown characteristics showed that the N treatments resulted in increased leaf area primarily through the production of greater numbers of leaves (Coyne and Van Cleve, 1977). Although no current data on litterfall or root production for the various fertilizer treatments are available to document directly the impact of improved tree growth, increased surface soil organic matter content probably reflects increased primary production (top and root material) by the aspen and the very sparse shrub layer. Lack of marked effect of nutrient additions on organic matter content in the 15- to 30-cm mineral soil depths may generally reflect the shallower rooting habit of the trees and the importance of above-ground plant parts in contributing organic matter for eventual incorporation into surface layers of the mineral soil.

Since mineral soil particle size did not vary markedly across the study site, changes in soil organic matter content in relation to fertilizer treatment assume more significance with regard to increased soil moisture retaining capacity and increased soil nutrient retention (cation exchange capacity). For the 0- to 15-cm soil depth, an average increase in percent organic matter occurred from 3.5% for the control to 4.9% for the N and P treatments. Because of the fairly high correlation between organic matter content and cation exchange capacity (CEC) encountered for other soils supporting aspen in this region of Alaska ($r^2 = 0.76$, range 30 to 10 meq/100 g for surface soil to 70-cm depth, respectively), this could be translated to a 16% increase in CEC or soil cation retention associated with the organic matter.

With the exception of the K treatment, results from this study suggest that higher organic matter content provided greater energy reserves for microbial activity. Associated with additions of organic matter from increased primary production would be increased energy reserves contributed by dead microbial tissue produced during sample processing prior to analysis. This source of substrate would be a consistent effect across all samples, modified by the presence of greater amounts of microbial tissue in samples which received N and P treatments compared with those which received K treatments and the control. Regardless of changes in soil organic matter content, these correlations appear to be mediated to a marked degree by higher soil N and P content (Table 3). This trend is especially evident at the 15- to 30-cm level where little absolute difference is evident in soil organic matter content between treatments, but respiration increased following repeated nutrient additions (Tables 1 and 2). It appears that the microbial population at this soil depth may be nutrient limited for the given level of energy reserves available for their metabolism. The leaching from surface soil layers of soluble organic constituents cannot be ruled out with regard to increased biological activity.

For the K treatments, the negative correlation between

soil respiration and organic matter content in the surface soil may reflect the impact of increased retention of K^+ and especially Cl^- to levels inhibitory to soil microbial activity (Table 1, Fig. 1). Fertilization with KCl alone resulted in insignificant changes in soil organic matter content and respiration in surface and subsurface layers, respectively, (Table 2). Lack of increase in surface soil respiration is associated with increased exchangeable K^+ and water extractable Cl^- (Tables 2 and 3). As noted earlier, the main effect that analysis of variance (ANOVA) shows is that prolonged fertilization with KCl resulted in an overall significant decrease in surface soil biological activity (Table 1). Concentration of K^+ and Cl^- in the soil solution may be further increased in treatments where N and K are combined through greater loss of soil water by increased transpiration due to increased tree leaf surface area in response to addition of N (Coyne and Van Cleve, 1977).

Lack of stimulation or negative effects of fertilization with chloride salts on soil organic matter mineralization have previously been reported (Greaves and Lund, 1921; Singh et al., 1969; Agarwal et al., 1971; Sandhu and Moraghan, 1972, Ryan and Sims, 1974; El-Shinnawi and Seifert, 1975). However, the mechanism for reduced activity has not been clearly established. Increased soil solution salt concentration and associated osmotic pressure would reduce water availability (increase total soil moisture potential) for microbial activities. Cell plasmolysis could occur at higher osmotic concentrations (Broadbent, 1965). High soil concentrations of K^+ and Cl^- might also affect microorganisms in a manner similar to effects on higher plants, that is, interfere with absorption of other nutrient elements, disrupt intercellular metabolic reactions, and damage cell organelles (Epstein, 1972).

A further change in substrate quality encountered in the form of increased soil acidity, primarily for N and K treatments, may reflect a combination of higher plant and microbial metabolic activities: (i) microbial oxidation of NH_4^+ to NO_3^- with associated production of acidity, and (ii) plant uptake of NH_4^+ and K^+ with hydrogen ions replacing the two nutrient elements in the soil (Moore, 1974). Uptake by plants of NO_3^- and Cl^- may have reduced acidity by replacement of OH^- or HCO_3^- in the soil solution. Acidifying effect on soil of NH_4NO_3 fertilization has been reported by Owensby et al. (1969) and Laughlin et al. (1976) for fertilizer trials in Alaska. In the former study, high rates of N fertilization (220 kg N/ha) lowered pH in the 0- to 15-cm soil layer from 5.9 to 4.7. In the Alaskan trials, yearly application of NH_4NO_3 at the rate of 267 kg N/ha for 4 years to a Knik silt loam (Typic Cryorthent) in southcentral Alaska resulted in a reduction in pH from 5.2 to 4.3 in the surface 5 cm of soil and from 6.4 to 5.4 in the 5- to 10-cm level of soil during the 4-year period.

In the present study, general improvement in rates of soil organic matter mineralization may indicate more rapid turnover of nutrient elements in the soil. Tree growth response to fertilization indicates that microbial nutrient immobilization, with resulting deficiency levels of nonfertilizer nutrients, probably did not occur or occurred to a degree insufficient to offset substantial growth. More rapid mineralization of organic matter is of particular importance in cold-dominated soils where increased nutrient turnover would mean improvement in reserves of available nutrients for tree growth which were not supplied with fertilizers. Reduced rates of organic matter mineralization, observed in the K treatments, could eventually result in nonfertilizer nutrient deficiencies and reduced tree growth (Table 1). In addition, if forest floor thickness and insulation of the mineral soil increase because of reduced organic matter mineralization, the benefits of increased tree growth through fertilization might be offset by a gradual reduction in soil temperature.

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